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Geologic map of the east-central Meadow Valley Mountains, and implications for reconstruction of the Mormon Peak detachment, Nevada

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ABSTRACT

The role of low-angle faults in accommodating extension within the upper crust remains controversial because the existence of these faults markedly defies extant continuum theories of how crustal faults form, and once initiated, how they continue to slip. Accordingly, for many proposed examples, basic kinematic problems like slip direction, dip angle while active, and magnitude of offset are keenly debated. A well-known example is the Miocene Mormon Peak detachment and overlying Mormon Peak allochthon of southern Nevada (USA), whose origin and evolution have been debated for several decades. Here, we use geologic mapping in the Meadow Valley Mountains to help define the geometry and kinematics of emplacement of the Mormon Peak allochthon, the hanging wall of the Mormon Peak detachment. Pre-extension structural markers, inherited from the east-vergent Sevier thrust belt of Mesozoic age, are well suited to constrain the geometry and kinematics of the detachment. In this study, we add to these markers a newly mapped Sevier-age monoclinal flexure preserved in the hanging wall of the detachment. The bounding axial surfaces of the flexure can be readily matched to the base and top of the frontal Sevier thrust ramp, which is exposed in the footwall of the detachment to the east in the Mormon Mountains and Tule Springs Hills. Multiple proxies for the slip direction of the detachment, including the mean tilt direction of hanging wall fault blocks, the trend of striations measured on the fault plane, and other structural features, indicate that it is approximately S77°W (257°). Given the observed structural separation lines between the hanging wall and footwall, this slip direction indicates 12–13 km of horizontal displacement on the detachment (14–15 km net slip), lower than a previous estimate of 20–22 km, which was based on erroneous assumptions in regard to the geometry of the thrust system. Based on a new detailed map compilation of the region and recently published low-temperature thermochronologic data, palinspastic constraints also preclude earlier suggestions that the Mormon Peak allochthon is a composite of diachronously emplaced, surficial landslide deposits. Although earlier suggestions that the initiation angle of the detachment in the central Mormon Mountains is ~20°–25° remain valid, the geometry of the Sevier-age monocline in the Meadow Valley Mountains and other structural data suggest that the initial dip of the detachment steepens toward the north beneath the southernmost Clover Mountains, where the hanging wall includes kilometer-scale accumulations of volcanic and volcaniclastic strata.

INTRODUCTION

In materials obeying Coulombic- or Byerlee-type failure laws, both the initiation and continued slip on normal fault planes dipping <30° is prohibited, assuming the maximum principal stress direction is subvertical (e.g., Collettini and Sibson, 2001; Axen, 2004). Extensional detachments (nominally, low-angle normal faults with displacements of kilometers to tens of kilometers) are widely described in the literature and currently accepted by most earth scientists as fundamental tectonic elements (e.g., Lister and Davis, 1989; Abers, 1991; Rigo et al., 1996; Chiaraluce et al., 2007; Bidgoli et al., 2015). However, they are problematic, not only from a mechanical point of view, but also from the point of view of historical seismicity, which is dominated by slip on planes steeper than 30° (e.g., Jackson and White, 1989; Wernicke, 1995; Elliott et al., 2010; Styron and Hetland, 2014). Thus, despite general acceptance, the very existence of low-angle normal faults continues to be challenged, in some cases even on geological grounds (e.g., Miller et al., 1999; Anders et al., 2006; Wong and Gans, 2008).

A frequently cited example of an upper-crustal normal fault that both initiated and slipped at low angle (20°–25°) throughout its evolution is the middle Miocene Mormon Peak detachment of southern Nevada (USA), which localized near the frontal thrust ramp of the Cretaceous Sevier fold-and-thrust belt (Figs. 1 and 2; Wernicke et al., 1985; Wernicke and Axen, 1988; Axen et al., 1990; Wernicke, 1995; Axen, 2004; Anderson et al., 2010). This interpretation has been challenged by several workers who contend that the hanging wall of the detachment constitutes one or more large-scale landslide or rock avalanche deposits (e.g., Carpenter et al., 1989; Anders et al., 2006; Walker et al., 2007).

Because the detachment is superimposed on the frontal ramp of a décollement fold-and-thrust belt, numerous potential structural markers provide constraints on both the initial dip and net displacement along the detachment. The most important of these include (1) the axial surfaces of the frontal ramp syncline and anticline, (2) footwall cutoffs of Paleozoic and Mesozoic stratigraphic

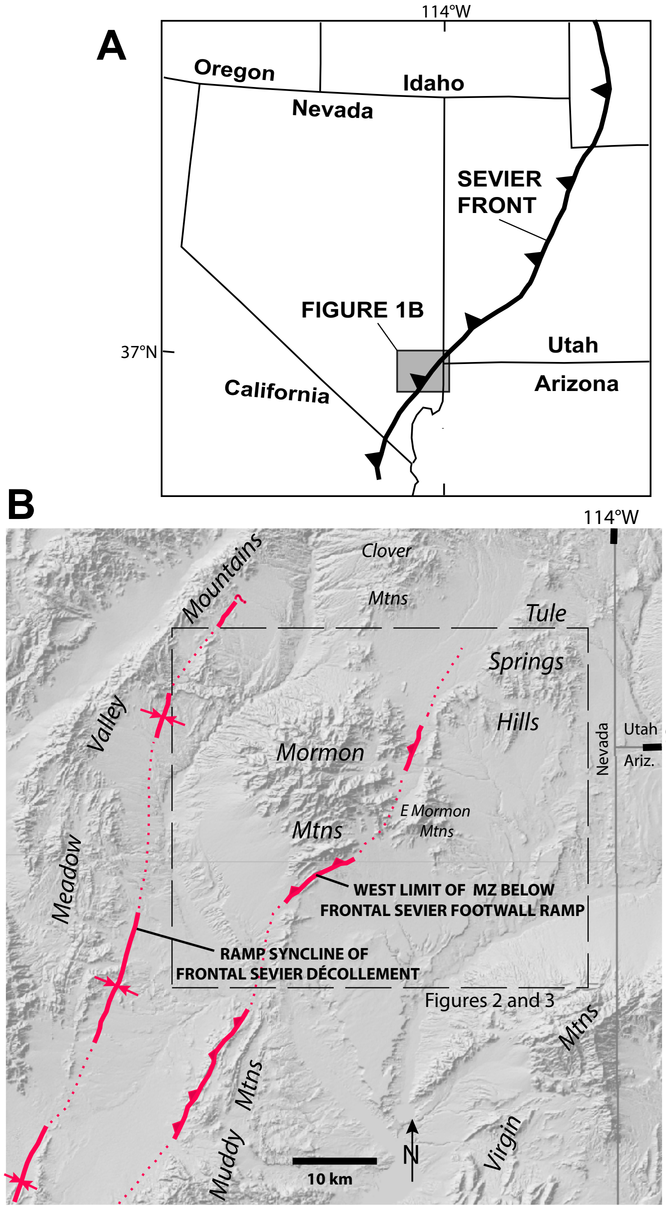

Figure 1. (A) Map showing the trace of the Sevier orogenic front (western USA) and location of B. (B) Shaded relief map showing the surface traces (solid) and subsurface projections (dotted) of the positions of selected elements of the frontal Sevier thrust fault in southern Nevada and environs, and the location of Figures 2 and 3. MZ—Mesozoic; Ariz.—Arizona.

units by the ramp zone, and (3) stratigraphic mismatch between the footwall and hanging wall of the detachment. Although some of these features were previously described in detail from the footwall of the detachment in the Mormon Mountains and Tule Springs Hills area (Fig. 1; Wernicke et al., 1985; Axen et al., 1990), potential offset counterparts in the Meadow Valley Mountains, immediately to the west of the Mormon Mountains, have to date only been mapped in reconnaissance (Tschanz and Pampeyan, 1970; Pampeyan, 1993). These maps depict a large-scale, monoclinal flexure in Paleozoic and Mesozoic strata overlain in angular unconformity by a succession of mid-Tertiary lacustrine and volcanic strata. Based on the regional geology of the frontal Sevier ramp zone in southern Nevada (Longwell et al., 1965; Burchfiel et al., 1974, 1982, 1997; Carr, 1983; Axen, 1984), the monoclinal flexure constrains the geometry of the frontal thrust ramp that generated it (e.g., Axen et al., 1990). In this paper, we present new 1:24,000-scale mapping, cross-sections, and structural reconstructions of the central Meadow Valley Mountains, targeted toward documenting the heretofore poorly constrained geometry of the frontal ramp zone above the detachment. We then examine these data in light of previous structural and thermochronological studies in the Mormon Mountains and Tule Springs Hills and explore implications for the existence, geometry, and kinematics of the Mormon Peak detachment as a typical low-angle normal fault.

GEOLOGIC SETTING

The Sevier front in the southern Nevada region (Fig. 1) is primarily expressed by a décollement thrust formed in Middle Cambrian dolostones, which can be traced along a strike length of >200 km (Fig. 1; Burchfiel et al., 1982; Bohannon, 1983; Axen et al., 1990). In the northern 50 km of exposure, the thrust trace is comparatively straight, striking NNE (Fig. 1), except where strongly overprinted by Miocene fault systems, such as the Mormon Peak detachment and other normal faults (Fig. 2). The most readily identifiable structural element along the entire trace of the thrust is the frontal ramp, where the thrust cuts upsection in the footwall from lower Paleozoic to Jurassic strata. The ramp zone is variably accompanied by a footwall syncline and thin duplex slices. The hanging wall of the thrust is invariably detached within a restricted stratigraphic interval within Middle Cambrian dolostones, near the boundary between the Papoose Lake and Banded Mountain Members of the Bonanza King Formation (Burchfiel et al., 1982; Bohannon, 1983; Wernicke et al., 1985; Axen et al., 1990).

The three structural elements of Sevier age that are most useful as potential offset markers along the Miocene detachment are (1) the base of the ramp and associated ramp syncline; (2) the intersection of the ramp and the top of footwall Mississippian strata; and (3) the top of the ramp and associated ramp anticline (Fig. 3). Based on previous mapping, the positions of the first two of these elements is well known. The top of the ramp in the footwall of the detachment is also well exposed, but the corresponding ramp anticline in the hanging wall of the detachment had not been recognized (Fig. 3).

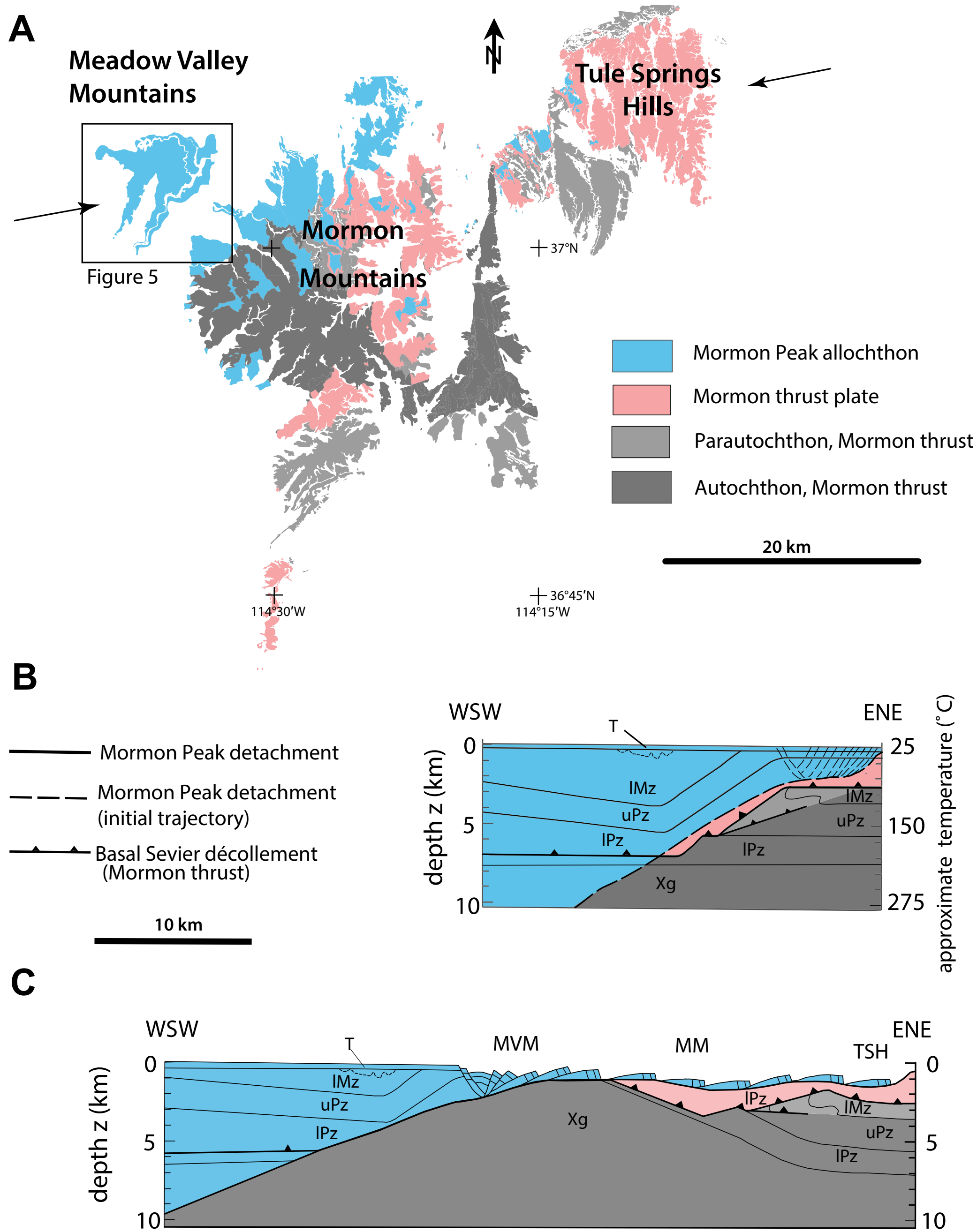

Figure 2. Structural map (A) and schematic cross-sections, restored (B) and unrestored (C) with respect to Miocene extension, of the Meadow Valley Mountains (MVM), Mormon Mountains (MM), and Tule Spring Hills (TSH) of Nevada. Arrows show the cross-section location. Xg—Proterozoic gneiss; lPz—lower Paleozoic strata; uPz—upper Paleozoic strata; lMz—lower Mesozoic strata; T—Tertiary strata. Map location is shown on Figure 1B. Black outline in A indicates the area of Figure 5.

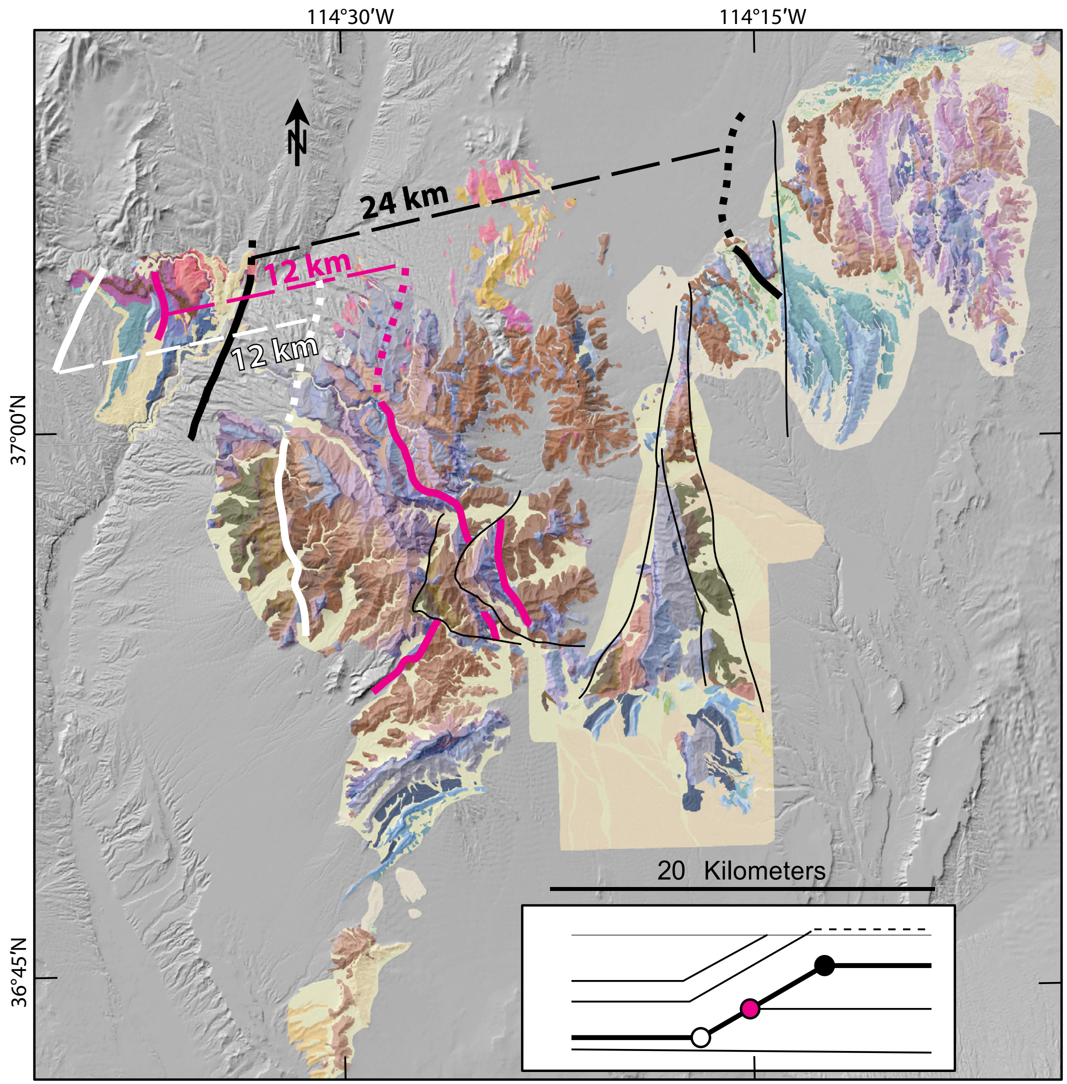

Figure 3. Map of the same area in Figure 2A showing locations of the Sevier ramp syncline (white line), thrust truncation of the top of Mississippian strata in the footwall (pink line), and the ramp anticline (thick black line). The three lines in northwestern corner of the map are above the detachment; lines in the central and eastern part of the map are below the detachment. Lines are dotted where projected. Thin black lines show major post-detachment normal faults. Dashed lines show offsets of structural features along the Mormon Peak detachment slip direction. Inset shows a schematic cross-section of a thrust ramp, showing positions of the offset thrust ramp features. Colors: Olive, Proterozoic basement; browns, Cambrian–Ordovician; lavender and blues, Devonian–Permian; greens, Mesozoic; purples and orange, Tertiary; yellow, Quaternary.

The Paleozoic and Mesozoic strata involved in thrusting lie along the eastern margin of the Cordilleran miogeocline. The hanging wall of the frontal thrust contains a section transitional between thin cratonic facies to the east and thick continental shelf deposits to the west (e.g., Burchfiel et al., 1974). Among a number of systematic across-strike stratigraphic features near the thrust ramp, the westward erosive pinchout of some 400 m of Permian carbonates (Toroweap and Kaibab Formations), below an unconformity at the base of the Lower Triassic Virgin Limestone Member of the Moenkopi Formation, is the most conspicuous (Burchfiel et al., 1974; Tschanz and Pampeyan, 1970). The pinchout occurs within the west-facing monoclinal flexure formed by the ramp and is best exposed in the central Meadow Valley Mountains and the Spring Mountains to the southwest.

The Mormon Mountains are a topographic and structural dome, veneered by klippen of the Mormon Peak detachment (Fig. 2). It is geometrically similar to a Cordilleran metamorphic core complex, except the level of footwall exhumation has not unroofed metamorphic rocks to the surface (Wernicke et al., 1985; Bidgoli et al., 2015). The footwall geology of the detachment is a 6–8-km-thick, variably east-tilted crustal section through the frontal thrust ramp zone. Below the detachment, the structurally deeper, western part of the Mormon Mountains exposes autochthonous Proterozoic basement and nonconformably overlying Cambrian through Mississippian strata. In the central part of the range, Middle Cambrian strata of the Cretaceous Mormon thrust plate (as distinct from the Tertiary Mormon Peak allochthon, described below) are thrust over Mississippian strata. In the eastern part of the range, the thrust ramps upward at an angle of 30°–40° relative to bedding in the autochthon (Fig. 2). Both the thrust and the Mormon Peak detachment are rotated eastward and cut by a younger set of west-dipping normal faults, known as the Tule Springs detachment system, described further below (Axen et al., 1990; Axen, 1993).

The hanging wall of the Mormon Peak detachment, hereafter referred to as the Mormon Peak allochthon, is composed of moderately to strongly tilted imbricate normal fault blocks (Fig. 2). The fault blocks are composed primarily of Cambrian through Pennsylvanian carbonates, all derived from the Mormon thrust plate. Along the northern flank of the range, the Pennsylvanian carbonates are concordantly overlain by interstratified gravels, rock avalanche deposits, and volcanic strata of Tertiary age, locally as much as 2000 m thick but generally much thinner (Anderson et al., 2010). Most of these strata are coeval with eruption of the middle Miocene Kane Wash Tuff (ca. 14–15 Ma), but locally, strata as old as the late Oligocene Leach Canyon Member of the Condor Canyon Formation (ca. 24 Ma) are preserved in the Tertiary section (Anderson et al., 2010). Apatite and zircon (U-Th)/He ages indicate that the footwalls of both the Tule Springs and Mormon Peak systems were unroofed primarily in middle Miocene time (ca. 14 Ma), contemporaneous with the extrusion of the Kane Wash tuffs and emplacement of rock avalanche deposits in the hanging wall of the Mormon Peak detachment (Bidgoli et al., 2015).

Stratal tilt directions within the Mormon Peak allochthon form a systematic pattern. The eastern and northern part of the allochthon contains blocks tilted to the east or northeast, and the westernmost part contains blocks tilted to the west or southwest (Figs. 2 and 4). Where the boundary between the east- and west-tilted domains intersects the northwest boundary of the Mormon Mountains, Tertiary strata are disconformable on Bird Spring Formation strata and exhibit both east and west tilts along with the underlying Paleozoic strata. Therefore, the difference in tilt directions within the allochthon in the Mormon Mountains is primarily a consequence of Miocene deformation (Anderson et al., 2010).

The Meadow Valley Mountains, immediately to the west of the Mormon Mountains (Figs. 1, 2 and 5), are separable into two distinct structural domains on the basis of the age of the youngest strata below the basal Tertiary unconformity. In the southern part of the range, the ramp syncline is cored by folded upper Paleozoic strata no younger than the Permian Kaibab Formation, overlain in angular unconformity by the Kane Wash Tuff (Pampeyan, 1993). Farther north, strata as young as the Jurassic Kayenta Formation are preserved beneath the Tertiary unconformity, suggesting at least a 1500 m difference in Mesozoic structural level near the axis of the syncline. In the northern area (central Meadow Valley Mountains), strata on the east limb of the syncline are overlain in angular unconformity by the Leach Canyon Member and younger strata. Toward the east, the sub-Tertiary unconformity progressively cuts downsection to the Bird Spring Formation of late Paleozoic age. Tertiary strata in the easternmost Meadow Valley Mountains lie in mild angular unconformity on the Bird Spring Formation. Still farther east in the northern Mormon Mountains, this same relationship (Oligocene unconformable on Bird Spring strata or overlying Permian red beds) holds for all exposures of Tertiary strata (Anderson et al., 2010).

METHODS

Geologic mapping of part of the Meadow Valley Mountains was done during the spring of 2011 and spring of 2012, using 1:12,000-scale base maps (Fig. 5). The following source geologic maps and unpublished field mapping were compiled and digitized in ArcGIS software: Meadow Valley Mountains mapping from this report (Fig. 5), Wernicke et al. (1985), Axen et al. (1990), Axen (1991, 1993), Taylor (1984), Ellis (1985), Olmore (1971), Skelly (1987), and Anderson et al. (2010); unpublished mapping in the northeastern Mormon Mountains (G. Axen, M. Skelly, and B. Wernicke, 1987); and unpublished mapping in the northwestern Mormon Mountains (B. Wernicke, B. Ellis, and W. Taylor, 1983). Stereograms of bedding and foliations within the field areas were prepared using the freeware Stereonet 8 program (Cardozo and Allmendinger, 2013; Allmendinger et al., 2013).

STRUCTURES

Faults within the mapped areas of the Meadow Valley Mountains (Fig. 5) are predominantly NNE- to NNW-trending high-angle normal faults with moderate offsets (tens to hundreds of meters). Tertiary volcanic units are truncated by these faults, indicating a Tertiary age. There is a tight, pre-Tertiary anticline with a northwest trend in the central part of the mapped area. Subvertical orientations of the Permian strata in the core of the anticline directly underlie subhorizontal Tertiary strata.

The general orientations of strata within the southwestern half of the map area are different from those in the northeastern half, with the transition occurring across a zone of north-south–trending faults located in the middle of the map area (Fig. 5). The Paleozoic and Mesozoic units in the southwestern half form a homocline that on average dips ~40°NW, overlain by subhorizontal Tertiary strata. In the northeastern half, dips of pre-Tertiary strata are more variable but average 10°–20°NE. Tertiary strata generally dip 25°–50°NE, somewhat more steeply than underlying pre-Tertiary strata.

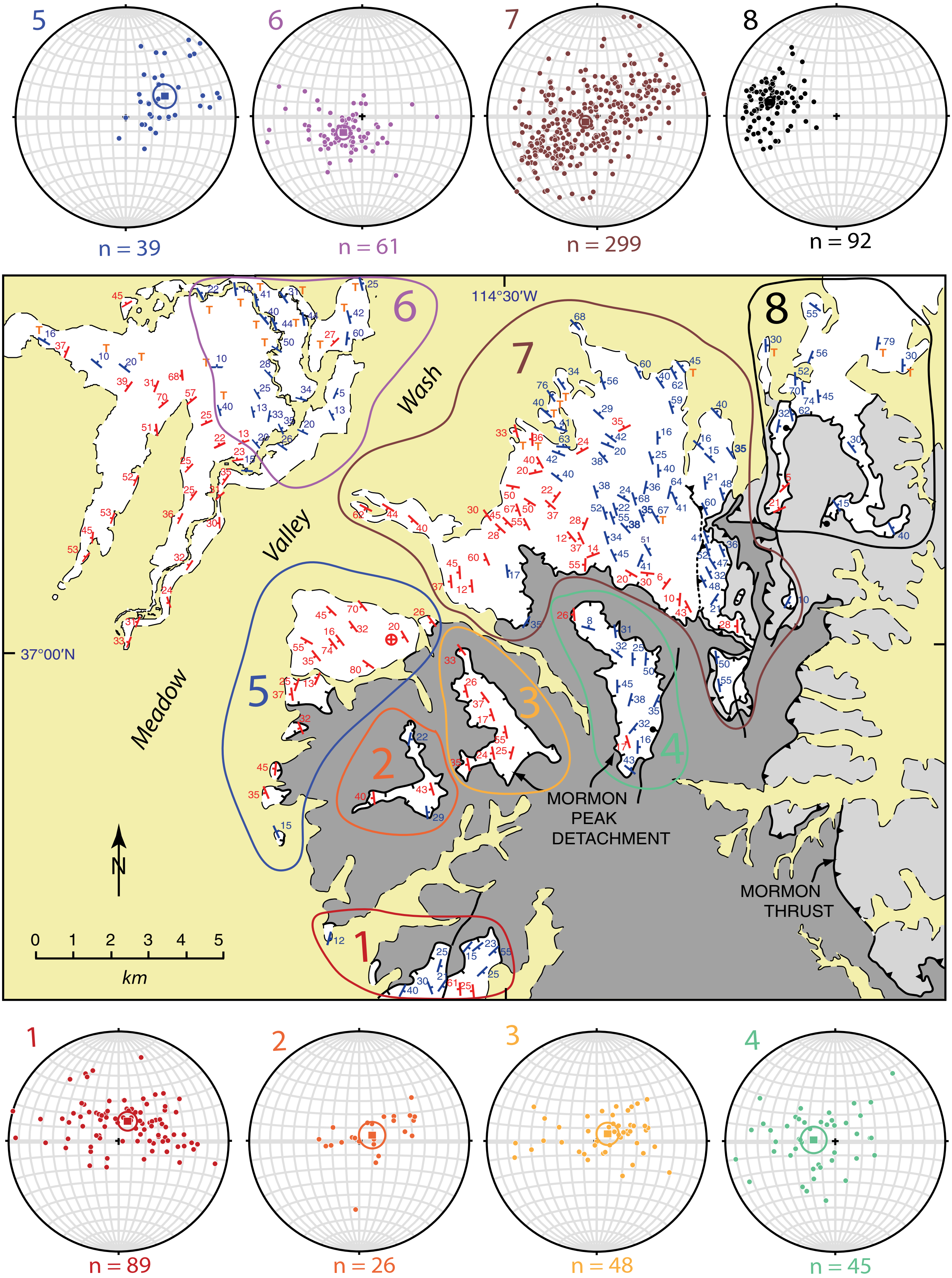

Figure 4. Map showing representative orientations of hanging-wall strata of the Mormon Peak detachment, with stereograms showing all measurements, grouped by areal domains. On the map, red symbols indicate west-dipping strata; blue symbols indicate east-dipping strata. Measurements within Tertiary strata are labeled with an orange T. Stereonet plots show orientations of poles to bedding, with each areal domain marked on the map by a number and boundary of the same color.

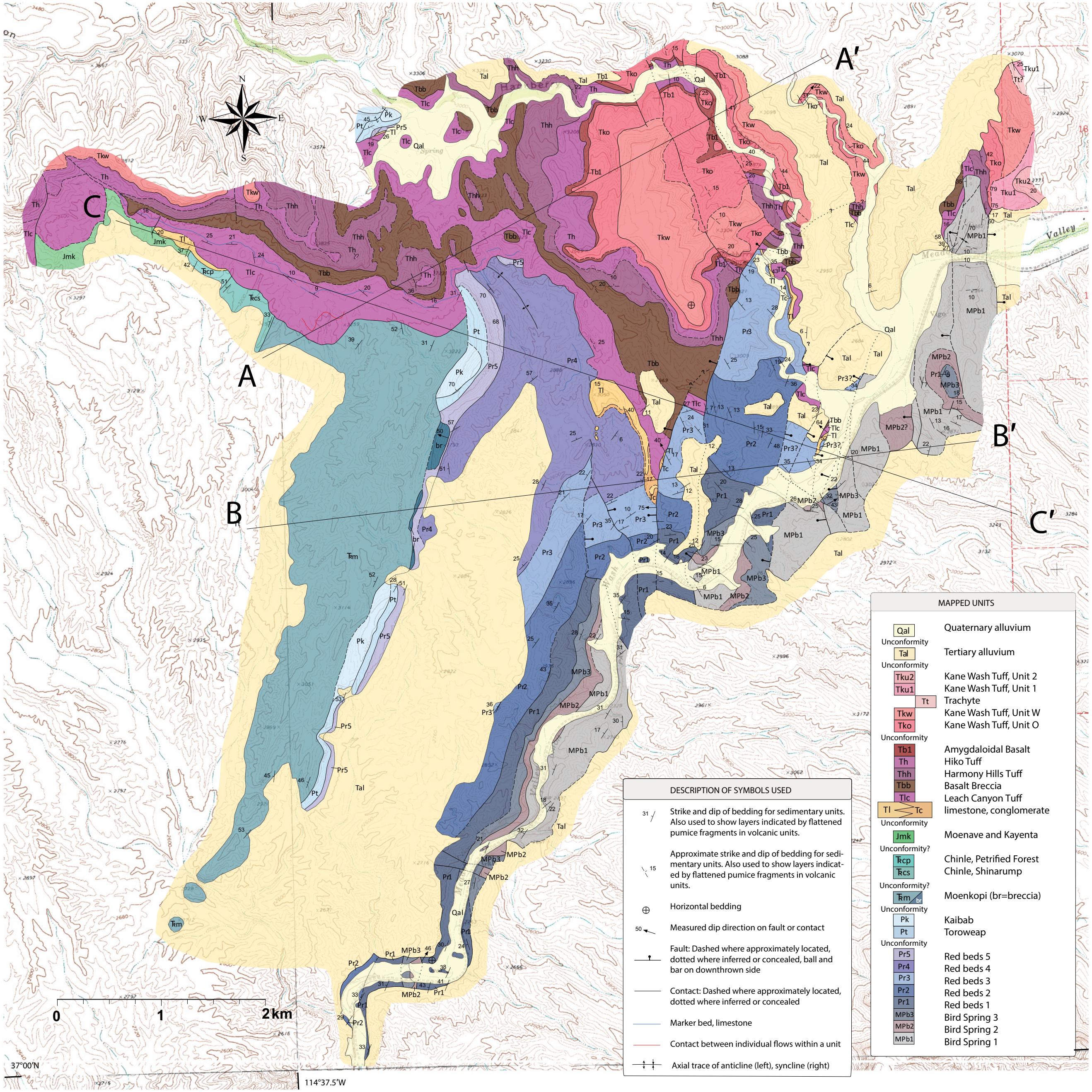

Figure 5. Geologic map of the Meadow Valley Mountains. All units are stratified, with ages indicated using standard North American symbols; see Appendix for unit descriptions. See Figure 2 for location. Cross-sections are shown in Figure 6.

The oldest exposed Tertiary units are assigned to the lower Quichapa Group (Leach Canyon and Bauers Members of the Condor Canyon Formation), locally overlying basal Tertiary conglomerate or lacustrine limestone (Pampeyan, 1993, and references therein). Leach Canyon tuffs overlie northwest-tilted Triassic and Jurassic formations in the west and cut downsection to the middle of the Permian red beds in the east. In the northeastern corner of the mapped area (Fig. 5), the Leach Canyon and Harmony Hills tuffs directly overlie Bird Spring strata, but it is unclear whether the contact is depositional or faulted. There appears to be a slight angular unconformity beneath and within Kane Wash units in the north-central part of the mapped area, suggesting that some tilting may have occurred between individual flows, but the difference in dip is too slight to be definitive.

Two cross-sections drawn perpendicular to the strike of Tertiary bedding (Figs. 6A and 6C) show the increase in Tertiary-age tilting toward the east. Reconstructions that untilt Tertiary strata and restore Tertiary fault offsets (Figs. 6B and 6D) show an eastward decrease in angle between the pre-Tertiary and Tertiary strata from west to east. Thus the area records the formation of a WNW-facing monoclinal flexure prior to deposition of the Tertiary section (Figs. 6B and 6D). After deposition, the flexure was overprinted by a NNW-trending extensional rollover structure, imparting an ENE dip onto the initial shallow west dip of the pre-Tertiary flexure. The pre-Tertiary monoclinal flexure is better shown by a cross-section, C-C′, drawn perpendicular to the strike of the monoclinal section (Fig. 6E). The section and its reconstruction (Fig. 6F) show the true dips of the Paleozoic and Mesozoic section before and after Tertiary tilting. They also reveal that the structural relief of the monocline is at least 4100 m, discussed in more detail below.

As noted above, orientations of bedding in the hanging wall of the Mormon Peak detachment show an abrupt transition from predominantly east dips to predominantly west dips in both the Meadow Valley Mountains and the Mormon Mountains (Fig. 4). The boundary between the two domains has an apparent separation of ~5 km left-laterally across a narrow swath of alluvial cover in Meadow Valley Wash (Fig. 4). The strike of bedding in fault blocks on the northwestern edge of the Mormon Mountains, closest to Meadow Valley Wash, is more westerly than in the interior of the Mormon Mountains, with the dip direction transitioning gradually between the two areas (Fig. 4).

As a potential proxy for the slip direction on the detachment, we compiled Tertiary tilt directions in the Mormon Peak allochthon, subdivided into eight domains (including the eastern domain in the Meadow Valley Mountains), with each domain denoted with variously colored and numbered enclosures in Figure 4. We do not include dips of hanging-wall strata in the western domain in the Meadow Valley Mountains, because these strata lie in sharp angular unconformity below subhorizontal Tertiary strata, and therefore their dips do not record the Tertiary tilt direction of fault blocks. In contrast, as mentioned earlier, west-dipping strata in the Mormon Mountains do contain Tertiary strata that are as strongly tilted westward as the underlying Paleozoic strata, and hence these are included in the compilation. Each klippe of the detachment is shown separately, except those with <20 measurements, which were combined with nearby klippen. Stereograms showing a total of 717 attitudes of bedding define a fabric in tilt directions oriented ENE-WSW. The main exception to this overall pattern is the strong east to ESE tilt in the northernmost Mormon Mountains (domain 8, Fig. 4).

The pre-Tertiary monoclinal flexure is apparent not only in the restorations of cross-sections through the Meadow Valley Mountains (Figs. 6B, 6D, and 6F), but also in stereographic restoration of Tertiary tilting of pre-Miocene strata in the greater hanging-wall area of the Mormon Peak allochthon (Fig. 7). Domains 7 and 8 (Fig. 4) in the northern Mormon Mountains, and the northeastern and southwestern portions of the Meadow Valley Mountains (domain 6 and the unnumbered area, respectively, in Fig. 4), all have Tertiary strata in depositional contact with underlying Paleozoic units. We calculated the mean Tertiary attitude in each domain and used it to estimate attitudes of bedding in Paleozoic and Mesozoic units in each domain prior to Tertiary deposition (Fig. 7). These restored dips define a northwest-facing monocline, with dips shallowing to a subhorizontal orientation in the northwestern Mormon Mountains (domain 7, Fig. 4). Restored dips in the westernmost Meadow Valley Mountains average ~35°NW, in the eastern Meadow Valley Mountains ~20°NW, and in the northwestern Mormon Mountains <10°. The reconstructed dips from the northernmost Mormon Mountains (domain 8) vary from this pattern, dipping ~25°S. Regardless of this complexity, the observation that the Tertiary section typically rests on the lower part of the Bird Spring Formation throughout the northern Mormon Mountains suggests limited overall pre-Tertiary structural relief east of the monoclinal flexure.

We can reconstruct offset on the Mormon Peak detachment at the latitude of the study area by relating the footwall and hanging-wall structural cutoffs (Fig. 3). The footwall cutoffs are exposed at the surface in the Mormon Mountains, and the location of hanging-wall cutoffs may be estimated by the downward projection of structural elements in the cross-sections in the Meadow Valley Mountains (Fig. 8). The geology of the Mormon Mountains and Tule Springs Hills in the footwall of the Mormon Peak detachment is modified from Axen et al. (1990), and the Meadow Valley Mountains geology is based on structural cross-sections from this study.

DISCUSSION

Transport Direction and Timing of Emplacement of the Mormon Peak Allochthon

Tilt Directions

Because the offset features are planar and therefore only permit an estimate of fault separation, proxies for the direction of displacement are necessary in order to estimate the net offset across the Mormon Peak detachment. The average of a number of independent proxies for slip direction suggests that the transport direction is ~S77°W (Table 1). The first proxy is Tertiary tilt

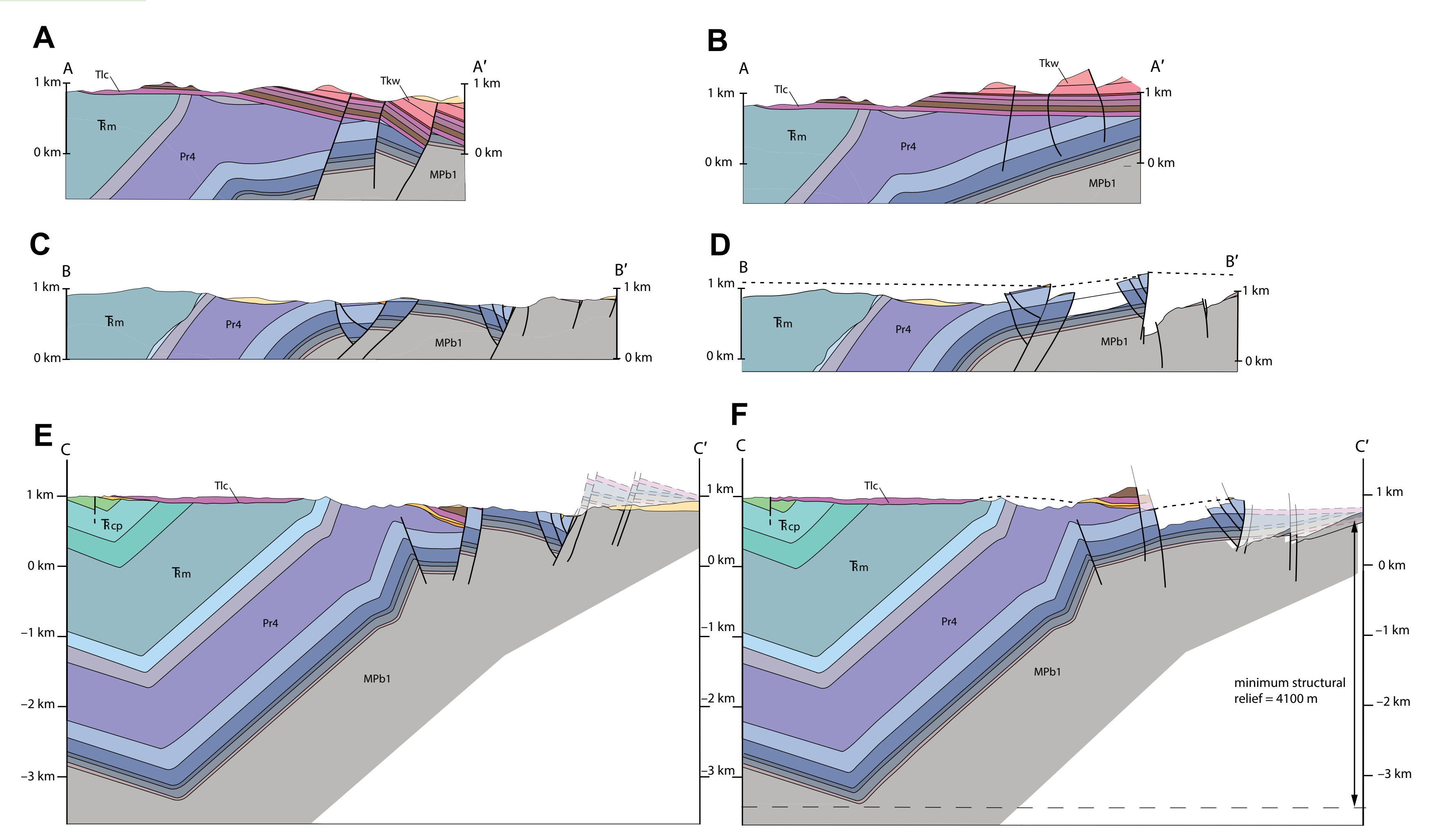

Figure 6. Cross-sections through the Meadow Valley Mountains, and reconstructions to early Miocene structural geometries. See Figure 5 for cross-section locations and legend. (A) Cross-section along line A-A′. (B) Reconstruction of A-A′. (C) Cross-section along line B-B′. (D) Reconstruction of B-B′. (E) Cross-section along line C-C′. (F) Reconstruction of C-C′. Dashed lines indicate projected position of base of Tertiary volcanic section. No vertical exaggeration. Thin dashed lines near point C′ indicate positions of late Paleozoic units projected onto the cross section.

directions within the Mormon Peak allochthon, based on the compilation of 717 attitudes of bedding within the hanging wall of the detachment that indicate the tilt directions within the Mormon Peak allochthon (Fig. 4). Studies of imbricate normal fault blocks suggest that the mean tilt direction tends to parallel slickenlines and other transport indicators (e.g., Anderson, 1971; Davis et al., 1980; Davis and Hardy, 1981). Thus, the tilt direction of bedding is often used as a proxy for maximum elongation direction in extensional allochthons, and for the transport direction on underlying detachments, assuming bedding was subhorizontal at the onset of extension.

The tilt directions reveal a strong preferred orientation. Figure 9A shows the modern orientations of pre-Tertiary strata that were subhorizontal prior to extension (i.e., excluding units from the Sevier thrust ramp in the southwestern Meadow Valley Mountains). The density contours and maximum density of these data show a well-defined ENE-WSW trend, with the best-fit

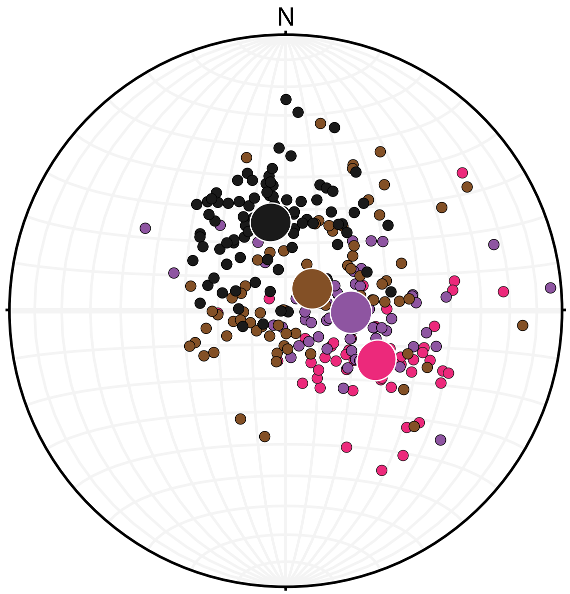

Figure 7. Restored poles to bedding in pre-Tertiary strata, taken from areas where Tertiary strata are exposed in the Mormon Peak allochthon. From west to east, these areas include the western Meadow Valley Mountains (magenta), domain 6 from Figure 4 (purple), domain 7 from Figure 4 (brown), and domain 8 from Figure 4 (black). Attitudes were restored by rotating nearby Tertiary units to the horizontal about the strike of bedding. The larger circles are the average orientation within each group, with the circle diameters scaled to the scatter within the data set. Data define a northeast-trending anticlinal flexure. Sources: this study (purple and magenta groups), B.P. Wernicke et al. (unpub. data; brown group), and Anderson et al. (2010; black group).

circle through them oriented 251°/86° (first number indicates azimuth of dip direction or plunge direction; second number indicates dip or plunge) (Fig. 9B), suggesting a maximum elongation direction and slip direction along the detachment of S71°W (azimuth 251°). In addition, the averages for each spatial domain (Fig. 4) define an array that also aligns along an ENE-WSW trend of S65°W (245°), excluding domain 8. Domain 8 is at the extreme northern edge of the Mormon Mountains. It contains a larger proportion of syntectonic strata and may have experienced complex vertical-axis rotations due to Tertiary strike-slip faulting and/or folding, as suggested by Anderson et al. (2010) and discussed further below.

In Figure 9C, poles to bedding for 90 attitudes measured in Tertiary units in the Mormon Peak allochthon are plotted, along with domainal averages (Fig. 4). A unimodal maximum in poles to bedding occurs at S69°W 60° (239°/60°), corresponding to a mean bedding attitude of N31°W, 30°NE. This implies an extension direction and transport of the allochthon of S59°W (239°) (Fig. 9D).

Fault Striations and the Radial Sliding Model

Twenty-six (26) striation measurements on or near the detachment plane, broadly distributed over the surface trace of the Mormon Peak detachment in the Mormon Mountains, are shown on Figure 10 (Walker, 2008). The east-plunging determinations were all measured on the east-dipping trace of the detachment in the eastern Mormon Mountains. As noted above, the detachment there was rotated eastward in Miocene time along imbricate normal fault blocks of the Tule Springs detachment system (Axen et al., 1990; Axen, 1993). The Tule Springs system faults cut, and are therefore slightly younger than, eastern exposures of the Mormon Peak detachment.

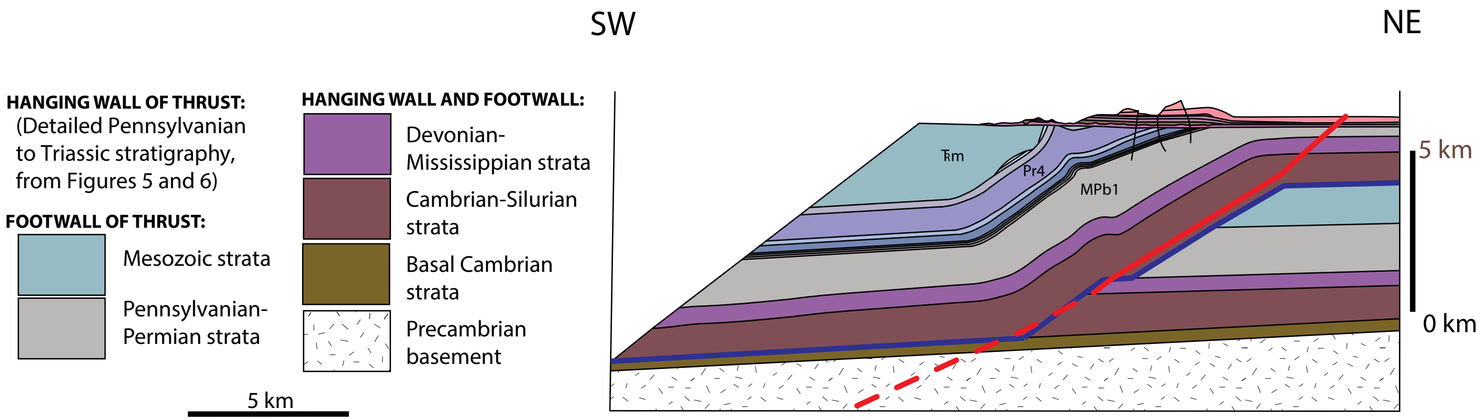

Figure 8. Regional reconstruction of pre-Tertiary structures in the Meadow Valley Mountains, Mormon Mountains, and Tule Springs Hills, drawn parallel to the WNW-ENE extension direction. Blue line is the Mormon thrust; red line is the Mormon Peak detachment. The thrust ramp shown with apparent dip of 32°; true WNW dip is 40°. Hanging-wall geology is based Figures 6B and 6F. Detachment footwall geometry modified from Axen et al. (1990).

TABLE 1. SUMMARY OF SLIP DIRECTION PROXIES, MORMON PEAK DETACHMENT

Data type	Inferred slip direction
Tilt direction in hanging-wall Paleozoic strata	251°
Tilt direction in hanging-wall Tertiary strata	239°
Mean trend of striations on fault surface	270°
Obtuse bisectrix, footwall conjugate fault fabric	260°
Intersecting fault offset direction	262°
Long axis of dome in detachment	250°

Walker et al. (2007) suggested that each of the individual klippen of the Mormon Peak allochthon represents an individual rock avalanche or surficial gravity slide mass that moved at a different time radially off of the modern dome, defined by the topography and by structural contours of the Mormon Peak detachment. They based their hypothesis on the claim that the striations everywhere indicate motion of the klippen down the modern dip direction of the detachment.

Across the eastern half of the topographic and structural dome, the substrate of the detachment is the Mormon thrust plate. The radial gravity slide hypothesis of Walker et al. (2007) is readily falsified by the observation that the oldest strata at the base of the fault blocks across the eastern half of the dome are everywhere younger than strata in the footwall of the detachment. Across this area, the detachment is a footwall décollement within the Bonanza King Formation, 100–200 m stratigraphically below the base of the Dunderberg Shale Member of the Upper Cambrian Nopah Formation (see Axen [1993] for stratigraphic nomenclature). The east-tilted normal fault blocks above the detachment across the eastern two-thirds of the Mormon Mountains are predominantly composed of Ordovician through Pennsylvanian strata, unconformably overlain by Tertiary volcanic and sedimentary strata, with only local preservation of the upper part of the Nopah Formation in some of the fault blocks, mainly in the westernmost blocks well to the west of the range crest (Fig. 11). The detachment level at the base of the hanging-wall blocks is thus stratigraphically at least 100–200 m above the basal beds of "unit Ꞓbb4" (the black marker horizon in the upper part of the Banded Mountain Member of the Bonanza King Formation, as defined in Wernicke [1982], Wernicke et al. [1985, 1989], Axen et al. [1990], and Axen [1993]), ruling out derivation of any of these blocks to the *west* of their present location, as required by the gravity-slide model. The footwall décollement in unit Ꞓbb4 can be confidently traced on geologic maps from the northeasternmost Mormon Mountains across the East Mormon Mountains and Tule Springs Hills to Jumbled Mountain (Axen et al., 1990; Axen, 1991, 1993). In the Tule Springs Hills, a few kilometers east of the Jumbled Mountain exposure, the detachment is observed to cut rapidly upsection in its footwall, from its unit Ꞓbb4 décollement upward across the Dunderberg Shale Member and into Upper Cambrian and younger strata (Axen, 1993).

Hence, basic palinspastic constraints define a simple stratigraphic separation across the detachment, independent of arguments based on offset structural markers of Sevier age. This stratigraphic separation constraint indicates that the pre-detachment substrate of fault blocks in the Mormon Peak allochthon lies in the Tule Springs Hills, east of the footwall cutoff of the Dunderberg Shale. This constraint requires the allochthon in its entirety to have been displaced westward, not radially off the crest of the present structural and topographic dome in the Mormon Mountains. The dome lacks a substrate that is compatible for the restoration of the hanging-wall blocks, precluding the top-east motions required by the radial model.

This simple "stratigraphic separation" argument is supported by the observations that (1) the tilted fault blocks in the eastern Mormon Mountains are bounded by faults that cut the Mormon Peak detachment, restoring its initial trajectory to dip uniformly westward (Wernicke et al., 1985; Axen et al., 1990); (2) the structural continuity between the northwest Mormon Mountains and the Meadow Valley Mountains, both of which are composed of ENE-tilted fault blocks of Kane Wash Tuff and older Tertiary strata resting unconformably on the lower part of the Bird Spring Formation (Figs. 3, 4, 5, and 6); (3) all of the blocks in the Mormon Peak allochthon, which are continuously exposed across the northern flank of the range and do not contain any thrust repetitions, are derived from the hanging wall of the Mormon thrust, as noted above; (4) the overall structural continuity of >700 measurements of stratal rotations in the allochthon form a coherent fabric traceable across all of the klippen (Figure 4); and (5) in both hanging wall and footwall, the structural and stratigraphic position of the detachment descends monotonically to the west.

A further difficulty with the surficial sliding model is the presence of a ~2000-m-thick Tertiary section within the Mormon Peak allochthon in the northernmost Mormon Mountains and southern Clover Mountains (Fig. 1; Anderson et al., 2010). This section is steeply tilted to the east and contains within it interstratified rock avalanche deposits. The unlikely implication of the gravity slide model is, therefore, that a slide block near the crest of the dome was, at first, a kilometer-scale depocenter receiving scarp breccias. Then at some later time it was uplifted and then slid into a newly developed depression.

The radial sliding model is also inconsistent with the recent thermochronometric data. These data indicate that the footwall of the detachment in the core of the dome was near the base of the partial retention zone for helium in zircon at ca. 14 Ma (~180 °C) and subsequently unroofed from paleodepths of 5–7 km (Bidgoli et al., 2015), depending on the geothermal gradient. This estimate of paleodepth confirms the cross-sectional reconstructions of Axen et al. (1990). The fault blocks in the allochthon represent at most the uppermost 2 km of the crust in pre-extension, middle Miocene time (e.g., Wernicke, 1995). Any model in which unroofing occurs by intra-range motion of putative slide masses therefore does not account for the magnitude of unroofing.

Against these straightforward kinematic and thermochronological arguments, the only evidence cited in support of radial gravity sliding are the 26 slickenline data, of which ~11 measurements (about 40% of the data collected, mainly along the northwestern flank of the range) plot in the northwest or

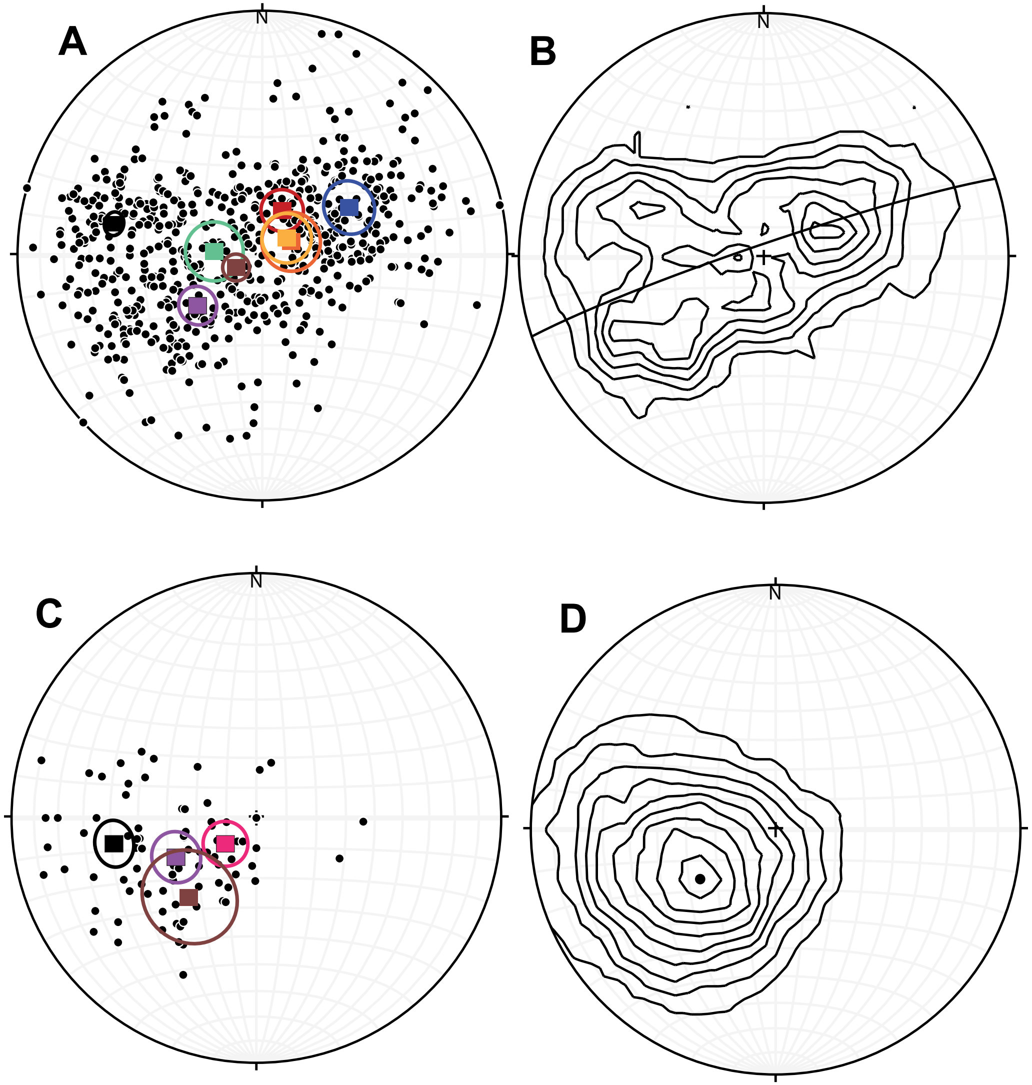

Figure 9. Equal-angle stereograms of orientations of strata within the hanging wall of the Mormon Peak detachment. (A) Poles to bedding of Paleozoic units (small black dots); squares are averages by domain, colored as in Figure 4. Circles show the relative spread of data within each subset. (B) Density contours of all points in A, and best-fit plane of 251/86, S71°W (azimuth 251°), 86°NW. (C) Poles to bedding of Tertiary units (small black dots); squares are averages by domain, colored as in Figure 4, with the addition of magenta for the western Meadow Valley Mountains. Circles show the relative spread of data within each subset. (D) Density contours of points in C, with center plunging S59°W61° (azimuth 239°).

southeast quadrant of a stereogram (Fig. 10B). As elaborated further below, this evidence is best interpreted as supporting arguments based on palinspastic constraints and the coherence of the structural fabric within the allochthon.

Commensurate with the palinspastically constrained westward displacement of the allochthon relative to its substrate, we assume that all of the striations plotted on Figure 10 reflect upper-plate displacement toward the western hemisphere of the stereogram. Neglecting the effect of post-detachment tilt along the eastern flank of the range, we interpret the western-hemisphere polarity of each of the measured striations to reflect the slip direction. A histogram of the western polarities (Fig. 10A) indicates that the striations define a unimodal population with the peak oriented east-west (270°), with an estimated standard deviation of ±37°.

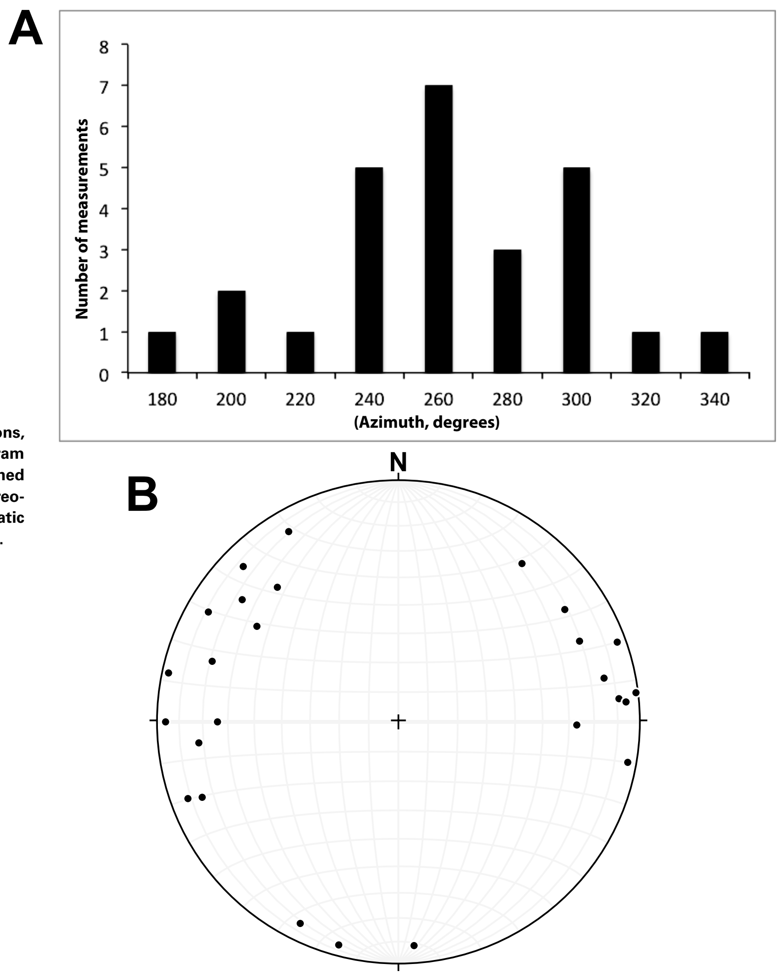

Figure 10. Orientation of fault striations, Mormon Peak detachment. (A) Histogram of kinematic orientation directions, binned in 20° increments. (B) Equal-angle stereogram, showing orientations of kinematic indicators. Data are from Walker (2008).

Other Indicators

Additional lines of evidence for the maximum elongation direction during extensional deformation in the Mormon Mountains (Wernicke et al., 1985) include (1) the observation that two intersecting normal faults in the footwall of the detachment do not offset each other, implying that both have a slip direction along or near the trend and plunge of their intersection, which is S82°W, 25° (262/25); (2) the trend of the obtuse bisector between two sets of syn-detachment, small-displacement high-angle faults in the footwall of the detachment interpreted to be conjugate fractures suggests that the least principal stress direction along the crest of the structural dome during fracture was S80°W (260°); and (3) the long axis of structurally domiform detachments is generally a reliable proxy for the extension direction along detachment faults (e.g., Davis and Coney, 1979; Spencer and Reynolds, 1991; Livaccari et al., 1993). The orientation of the long axis of the structural dome defined by the detachment is also approximately WSW (~S70°W [250°]); e.g., Walker et al., 2007, their figure 1).

A summary of all available slip direction indicators is presented in Table 1. The mean orientation of these proxies is S77°W (257°). This extensional slip direction is oblique (~40°) to the dip direction of the thrust ramp (N62°W [298°]), requiring caution in interpreting two-dimensional cross-sections depicting the interaction between Sevier-age and Miocene tectonic elements (e.g., Fig. 8). Below, given an overall WSW displacement direction for the Mormon Peak allochthon, we present data bearing on the fault separation of Mesozoic features by the detachment in map view (Fig. 3), so as to better assess the three-dimensional complexities of structural restoration.

Locations of Three Offset Sevier-Age Structural Markers

Above the Mormon Peak Detachment

The geometry of the Sevier-aged thrust ramp is defined by the west-facing monocline in the western part of the mapped area (Figs. 2 and 5). At the level of the basal Tertiary erosion surface, the monoclinal section between the axial surfaces of the bounding folds ranges from the lower Bird Spring Formation (Pennsylvanian) to the Moenave Formation (Jurassic). The reconstruction of a section perpendicular to the Sevier structure (Fig. 6F) shows the base of the MPb2 unit being 4100 m structurally higher at C′ than at C (see Fig. 5 for location). This provides a minimum amount of structural relief on the ramp. The total structural relief would be larger by the thickness of Bird Spring that is involved, something that is not readily measureable within the Tertiary fault blocks that are currently exposed in the area. The minimum amount of unit MPb (Bird Spring Formation) involvement would be 200 m, given the thicknesses exposed. The maximum would be 700–1000 m (Pampeyan, 1993; Axen, 1993). Thus, we estimate the total structural relief on the ramp to be between 4300 m and 5100 m.

Structural relief of 4300–5100 m on the monocline accords well with the value predicted by the structural relief on the frontal Sevier thrust ramp exposed in the detachment footwall, which is simply the thickness of the Middle Cambrian through Jurassic section exposed beneath the ramp. According to footwall cross-sections from the Tule Springs Hills and Beaver Dam Mountains to the east, the section is ~5000 m thick (e.g., Axen, 1993, his plate 1; Hintze, 1986, his plate 2A). A value near 5000 m is inconsistent with placing the base of the frontal thrust ramp in Mississippian strata, as depicted in the reconstruction of Axen et al. (1990). This placement predicts structural relief of only 3000 m in the hanging wall of the thrust. Their reconstruction was based on the occurrence of a Cambrian-on-Mississippian décollement segment of the thrust exposed in the central Mormon Mountains, which is cut off by the detachment.

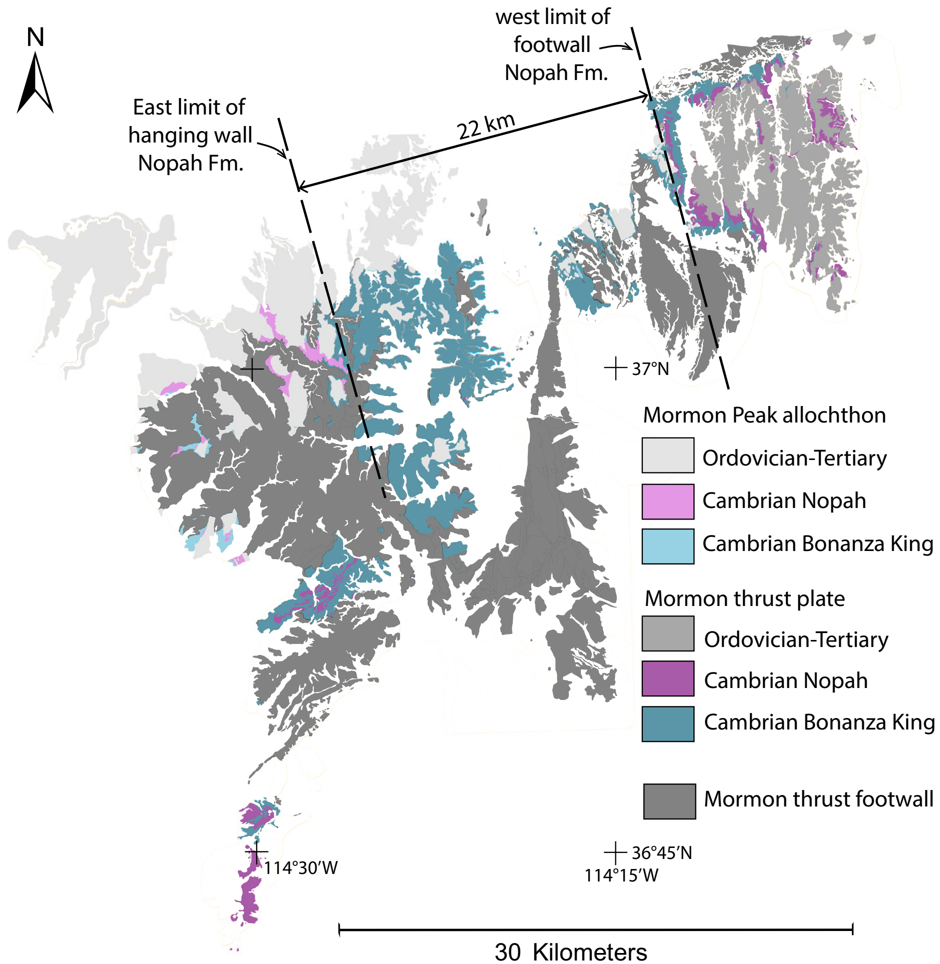

Figure 11. Map showing distributions of Cambrian Bonanza King Formation and Nopah Formation strata in the hanging wall and footwall of the Mormon Peak detachment, excluding autochthonous strata. West limit of footwall Nopah strata is presently 22 km east of the easternmost hanging-wall Nopah strata, defining a 22 km separation across the fault.

The exposed décollement segment is only ~2 km wide in the thrust transport direction. In the northern part of the range, the Mississippian décollement segment may die out altogether. A narrow footwall décollement segment within the Mississippian, however, appears to be useful as a structural marker, because it predicts significant structural effects in the hanging wall of the thrust, as elaborated on below.

A northward pinchout of a footwall décollement segment in Mississippian strata is supported by a change in the exposed structural level that occurs between the southern Meadow Valley Mountains and the area mapped in this study, as described in the Geologic Setting section. Along strike to the south of the area of Figure 5, the sub-Tertiary unconformity, rather than resting on strata as young as Jurassic, instead rests on strata only as young as the Permian Kaibab Limestone. This difference in stratigraphic position suggests a 1500 m difference in total structural relief on the ramp to the south, from about 4500 m to 3000 m. This difference is readily explained by a lateral ramp in the thrust, where a décollement riding on top of the Mississippian structurally descends to the Middle Cambrian to the north, dropping the structural level of the thrust plate toward the north by 1500 m, about the stratigraphic difference both between the Kaibab and Jurassic strata in the hanging wall, and between the Banded Mountain Member and the upper Mississippian strata in the footwall.

Given these constraints, the first structural marker is delineated by the western edge of the monocline (ramp syncline; Fig. 3). The west-dipping section above the ramp is complicated by the "East Vigo thrust" and other structural complexities identified by Pampeyan (1993), but it is clear that the structural low is defined by a narrow outcrop belt of Jurassic strata (point C, Fig. 5). The match in structural relief exposed in the central Meadow Valley Mountains and the relief on the footwall ramp also suggests that the axial trace of the syncline is located near the westernmost exposures of Jurassic strata (also near point C on Fig. 5), because a location further west would require more structural relief on the ramp than could be generated by the entire Cambrian through Jurassic section. Additional structural relief would require somehow building up structural relief in the footwall with additional thrusts or other structures, which are not observed in extensive exposures of footwall rocks in the region. Therefore we interpret the ramp syncline to be located at the western edge of the Moenave Formation exposures mapped here, near point C.

The second structural marker, which constitutes the most significant complication in the otherwise homoclinal section from lower Bird Spring to Moenave strata, is a relatively tight backfold that affects the central part of the section, which may have a relationship with the structures below the detachment.

The third structural marker, the trace of the ramp anticline, is located at the top of the ramp where the dip of the reconstructed pre-Tertiary units shallows from 40° to subhorizontal. Within the Meadow Valley Mountains, reconstructed pre-Tertiary units shallow eastward from 40° to 15°, but do not reach 0°, indicating that the anticline is located just east of the easternmost Meadow Valley Mountains exposures (Fig. 6). Consistent with this hypothesis, the stereographic plot of reconstructed dips in pre-Tertiary strata discussed above (Fig. 7) indicates that the hinge of the anticline is located between the Meadow Valley Mountains and the westernmost Mormon Mountains (Figs. 4 through 8).

Below the Mormon Peak Detachment

In the footwall, the first structural marker is the base of the ramp, i.e., the intersection of the axial surface of the ramp syncline with the Mormon thrust. It can be constrained only by its easternmost possible position, because the detachment mainly cuts downward across the thrust autochthon and into Proterozoic basement (Wernicke et al., 1985). The map-view position of the undisturbed, autochthonous base of the Middle Cambrian Banded Mountain Member of the Bonanza King Formation (the detachment horizon for the thrust décollement) marks the easternmost possible position of the base of the ramp (Fig. 3).

The second Sevier-age structural marker below the detachment is the location of the westward cutoff of footwall Mississippian strata by the thrust ramp (Figure 3). As described above, the thrust fault remains within the Mississippian for at least 2 km across strike, and is cut off by the Mormon Peak detachment (Figs. 2 and 8). In the hanging wall, we infer that the narrow Mississippian décollement segment of the thrust served as a nucleation point for the relatively tight anticlinal backfold within hanging-wall Permian strata (Fig. 5), as indicated by the reconstruction in Figure 8.

The third marker below the detachment is the top of the thrust ramp, which is well exposed in the Tule Springs Hills near Jumbled Mountain. To the west of it, the décollement ramps at a moderate angle across upper Paleozoic and lower Mesozoic strata. To the east, the thrust plate is everywhere thrust over the Jurassic Kayenta Formation (Axen, 1993).

Offset Estimates

Offset along the detachment is, in part, based on the six positions of the three Sevier-age structural markers described above, and summarized in Figure 3. Above the detachment, they are the axial traces of the ramp anticline and ramp syncline and the axial trace of a small backfold we infer to be genetically related to the narrow décollement segment of the thrust. Below the detachment, they are the base and top of the thrust ramp, and the intersection or cutoff of Mississippian strata along the thrust ramp. In present geometry, the anticline at the east edge of the Meadow Valley Mountains is 24 km away, as measured along the detachment slip direction, from the top of the thrust ramp at Jumbled Mountain (easternmost thick black line, Fig. 3). This includes the combined offset of (1) the Mormon Peak detachment and (2) younger faults in the footwall of the Mormon Peak detachment, predominantly the Tule Springs detachment system of Axen et al. (1990) and Axen (1993). Axen et al. (1990) estimated 11 km of slip on these faults based on restoration of cross-sections. Subtracting that figure from the 24 km of total separation of the ramp anticline leaves 13 km of horizontal component of slip on the Mormon Peak detachment.

The ramp syncline in the hanging wall is 12 km WSW of the east limit of its possible position in the footwall (Fig. 3). There may be minor strike-slip offset along Meadow Valley Wash, but this is at high angle to the detachment slip direction. Therefore, based on this marker alone, we estimate a maximum of 12 km of horizontal displacement on the detachment at this location. The position of the truncation of the Mississippian by the Sevier thrust and its narrow ramp zone, and its counterpart projected in the subsurface in the Meadow Valley Mountains, also suggests ~12 km of slip on the detachment.

Independent of any considerations of thrust ramp geometry, Anderson et al. (2010) proposed a 10–15 km of offset across the northern part of the Mormon Mountains, which they attribute to displacement on an inferred strike-slip fault. Within the Kane Wash section, they documented scarp breccias derived from both Cambrian- and Jurassic-aged bedrock. They noted that the nearest location where such disparate ages of source material could have been simultaneously exposed to a fault scarp is in the Tule Springs Hills, 10–15 km to the east-northeast. These landslides and interbedded Kane Wash volcanics both dip 70° to the east, a direction that would be expected from block rotation above the Mormon Peak detachment.

Independent of these structural markers, as mentioned above in regard to the uniform displacement direction of the detachment, the stratigraphic offset of the Dunderberg Shale Member of the Nopah Formation is defined by the east limit of Nopah Formation exposures above the detachment and by the truncation of the Dunderberg below the detachment (Fig. 11). The stratigraphic separation in the direction of transport is at least 22 km. Again, subtracting 11 km of offset along the younger Tule Springs detachment system, the net horizontal offset along the Mormon Peak detachment is at least 11 km.

Given these offsets, the scaling between displacement and fault length of the Mormon Peak detachment is comparable to one of the best known examples of an active low-angle normal fault, the Alto Tiberina fault of central Italy, which has a strike length of at least 70 km and net offset of 10 km (e.g., Mirabella et al., 2011).

Initial Dip of the Detachment

The initial dip of the detachment may be estimated by comparing its orientation with those of various elements in the thrust system, as well as its reconstructed angle with respect to the basal Tertiary unconformity in the area, which pre-dates formation of the detachment (e.g., Wernicke, 1995). In the central Mormon Mountains, the detachment makes an angle of 17° with respect to the autochthonous stratigraphy, based on a restored section ~20 km along strike to the south of our sections (Wernicke et al., 1985, their figure 15). Assuming a gentle west dip of the stratigraphy at the time of initiation of the detachment, then an initial dip of the detachment of 20°–25° is indicated.

Along our sections, the best datum for estimating the initial dip of the detachment is the thrust ramp and its relationship to the sub-Tertiary unconformity. Paleozoic units thrust over the ramp should correspond fairly closely to the dip of the ramp, assuming a simple reconstruction (Fig. 8). Bedding within the western Meadow Valley Mountains dips an average of 40°NW relative to the subhorizontal Tertiary units that overlie it. The base of the thrust ramp is not unambiguously exposed in the footwall in the Mormon Mountains, indicating that it has been (largely or) wholly excised by the detachment, which cuts directly into autochthonous basement in the westernmost Mormon Mountains (Wernicke et al., 1985; Axen et al., 1990). Whatever the case in the central and southern Mormon Mountains where most of the detachment footwall is exposed, relief across the monocline in the Meadow Valley Mountains demands that the ramp cut upward more or less uninterrupted from Middle Cambrian through Jurassic strata in the northernmost Mormon Mountains and southern Clover Mountains, where this area palinspastically restores (Figs. 3 and 8). Hence, if the Mormon Peak detachment is parallel to the ramp, then the initial dip of the Miocene detachment in this area should be ~40°. The reconstruction in Figure 8, oriented parallel to section A-A′ (Figs. 5 and 6), depicts the fault and ramp with a dip of 30°, accounting for apparent dip correction between the WSW extension direction and the WNW dip direction of the ramp.

This estimate is 15° steeper than the 20° to 25° initial dip proposed for the central Mormon Mountains (e.g., Wernicke et al., 1985; Wernicke, 1995). Hence, if we presume that the detachment tends to follow the thrust ramp to the north, its initial dip must steepen by 15° along strike toward the north, from 25° to 40°. A steeper detachment to the north, especially at uppermost crustal levels (<2 km; Fig. 8), would also tend to promote the creation of void space for a deep supradetachment basin, and promote the generation of scarp breccias, as observed in the northernmost Mormon Mountains. Our map compilation indicates that the detachment fault within the northernmost Mormon Mountains is closely parallel to the thrust ramp there. For at least 6.6 km in the inferred transport direction, the detachment is parallel to the ramp section, localized within the lower part of unit Ꞓbb4 of Wernicke et al. (1985).

As noted above, the 1500 m difference in structural relief between the central and southern Meadow Valley Mountains suggests a lateral ramp in the thrust, between an extensive Cambrian flat to the north and a significant Mississippian flat to the south. This lateral ramp would occur between the central and northern Mormon Mountains, and may have influenced the initial dip of the detachment, with a steeper dip of 40° to the north (consistent with the reconstruction in Fig. 8 and the detachment-ramp angle) and shallower dip to the south (consistent with the reconstruction of Axen et al. [1990] and the detachment-autochthon angle). Whereas the shallower, southern segment of the detachment would have had nearly pure dip slip at 25°, the northern segment would have had a strong component of left-oblique slip plunging 30° along a fault plane that dips 40°.

In addition to probable variations in initial dip for the detachment along strike, there may also be significant variation in the dip of the detachment and thrust as a function of depth. The 42° dips within the Moenkopi and Chinle may reflect a steeper, lower part of the thrust ramp, while the 30° dips of the Permian red beds and Bird Spring Formation may reflect a shallower upper ramp.

Post-Miocene Faulting

There is the potential for a few kilometers of left-lateral strike-slip motion to have been accommodated by a fault or faults buried within Meadow Valley Wash between the Meadow Valley Mountains and Mormon Mountains. This is suggested by (1) 5 km apparent offset of the boundary between east- and west-dipping strata noted earlier (Fig. 4) and (2) the apparent sinistral vertical-axis rotation in the dip direction of strata at the northwesternmost edge of the Mormon Mountains, closest to the Meadow Valley Wash. Possible right-lateral faulting in the northernmost Mormon Mountains is suggested by apparent dextral drag folding along an east-west–trending fault concealed beneath alluvium. The existence and timing of motion of these faults is speculative, as none of them have been identified in the field, but other north-trending, left-lateral faults, active after regional Miocene normal faulting, have been identified in the region. These include the Kane Wash fault on the western edge of the Meadow Valley Mountains, and the Tule Corral fault in the central part of the Tule Springs Hills (e.g., Axen, 1993; Anderson and Barnhard, 1993). Assuming one or more sinistral faults exist beneath Meadow Valley Wash, they do not have significant vertical offsets, because blocks on either side of their putative traces lie at the same structural level. On both sides of the wash, Tertiary volcanic rocks rest unconformably on the Bird Spring Formation.

Other Interpretations of the Mormon Peak Detachment

Some researchers have questioned, firstly, whether the Mormon Peak detachment is a "rooted" crustal fault, as opposed to a system of landslide deposits, as noted above (e.g., Anders et al., 2006; Walker et al., 2007); and secondly, whether all of the apparent thinning of the Mormon Peak allochthon is due to faulting, or alternatively, to large-scale dissolution of carbonate rocks (Anderson et al., 2010).

In addition to the stratigraphic and structural arguments against radial sliding described above, several other lines of evidence indicate that the detachment is rooted into the crust and accommodates regional extension. First, stable isotopic data on fault rocks on the detachment (Swanson et al., 2012) indicate that rapid circulation of significant volumes of warm meteoric fluids occurred during motion, from a depth of at least 4 km, too deep to explain with a landsliding mechanism. Second, the 2-km-thick section of multiple rock avalanche deposits interbedded with the Kane Wash Tuff in the hanging wall and their 70° dip toward the east (see Anderson et al., 2010) are suggestive of gradual syntectonic deformation at ca. 14 Ma, and remain poorly explained by catastrophic gravity sliding. Third, the stratigraphy and structural style of the easternmost Meadow Valley Mountains, ENE-tilted normal fault blocks of Bird Spring Formation unconformably overlain by Tertiary tuffs, is the same as that in the nearby Mormon Peak allochthon in the Mormon Mountains, and highly dissimilar to the exposed basement rocks below the detachment. Interpreting the Meadow Valley Mountains block as part of the detachment footwall, a consequence of the radial sliding model, requires the existence of two faults for which there is no evidence: (1) the base of the slide, which would oddly exhibit the same stratigraphy and structural style as its substrate in the runout zone, and (2) a pre-existing high-angle fault with kilometers of structural relief, presumably buried beneath the slide (Walker, 2008). Both putative structural boundaries would be fortuitously concealed beneath the ~2 km width of alluvial cover between the nearest approach of the two ranges (Fig. 4) without resulting in any significant contrast in stratigraphy, structural level, or structural style.

Evidence in favor of the detachment being a rootless fault, as noted above, mostly hinges on the radial orientations of a small number of fault striations measured on or near the detachment (Walker et al., 2007). However, such a distribution of slip directions, even assuming they are representative of a much larger population, does not preclude the detachment from being a rooted fault. Singleton (2013) described kinematic indicators on corrugations of the Buckskin-Rawhide detachment in west-central Arizona showing a radial pattern, which he interpreted as a reflection of a late-stage compressional event perpendicular to the extension direction, promoting flexural slip along the detachment plane. As argued in Wernicke et al. (1985) and Anderson and Barnhard (1993), the north-south component of bending of the Mormon dome resulted from regional north-south shortening during extension and emplacement of the Mormon Peak allochthon, which would promote north or northwest-trending flexural slip along the northern flank of the dome.

The determination of the amount of displacement and thinning accommodated by slip on the detachment, versus dissolution of the hanging wall (e.g., Anderson et al., 2010; Diehl et al., 2010), is more difficult to address directly with our data. Our approach is to present here a kinematic model based on reconstruction of the dismembered Mesozoic thrust system and does not depend on structural reconstruction of individual fault blocks in the Mormon Peak allochthon. Thus, although we acknowledge the central importance of fluid-assisted deformation in the development of the Mormon Peak and other carbonate allochthons (e.g., Swanson et al., 2012, 2016), it is beyond the scope of this paper to address this important issue.

CONCLUSIONS

Based on the mapping of structures within the Meadow Valley Mountains and a regional compilation of geologic data in the neighboring Mormon Mountains, East Mormon Mountains, and Tule Springs Hills, we correlate Sevier-age contractile structures across the Mormon Peak detachment and provide a new, independent estimate of 12–13 km of horizontal displacement at the latitude of the central Meadow Valley Mountains–northern Mormon Mountains. Accounting for a 30° plunge in the slip vector, net slip on the fault is estimated to be 14–15 km. This estimate is in the interpreted slip direction of S77°W (257°), which is based on multiple lines of structural evidence (Table 1).

The observations presented here are broadly consistent with the model of Axen et al. (1990), where a Sevier-age thrust flat-ramp-flat is overprinted and distended by the Mormon Peak detachment as well as by structurally lower, younger detachments. However, our data indicate several significant modifications to their geometric and kinematic model of the detachment. First, structural relief indicates that the flat at the base of the ramp is in Cambrian, not Mississippian strata, within the northernmost Mormon Mountains. Second, the total displacement on the Mormon Peak detachment is significantly less than the estimate of 20–22 km as indicated in the earlier reconstruction, but consistent with recent estimates based on thermochronological data (Bidgoli et al., 2015). Third, assuming the detachment initiated near the thrust ramp, it would have steepened northward from a dip of 20°–25° in the Mormon Mountains to a dip of 40°, over an along-strike distance of 10–20 km to the north.

ACKNOWLEDGMENTS

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APPENDIX. DESCRIPTION OF MAP UNITS

Descriptions of map units (Fig. 5) are heavily modified from Pampeyan (1993). All potassium-argon (K-Ar) ages cited have been recalculated using the decay constants presented by Steiger and Jäger (1977), resulting in ages 2.7% older than the original published data. Color terminology used in the following descriptions is from the National Research Council Rock Color Chart (Goddard et al., 1948).

Qal: Alluvium (Holocene)—Unconsolidated stream-channel and fan deposits of clay to cobble size. Commonly less than a few meters thick but probably exceeds 10 m in major washes.

Tal: Alluvium (Pleistocene? and Tertiary)—Mildly consolidated stream-channel and coarse basin deposits of sand to cobble size, crudely stratified. Commonly present on former drainage terrace surfaces or perched on older alluvial or lacustrine deposits. Thickness is 100 m at the mouth of Vigo Canyon, but typically thinner.

KANE WASH TUFF (Miocene)—Ash flows are subdivided, from youngest to oldest, into unit 2, unit 1, unit W, and unit O. Adularescent sanidine is diagnostic of this tuff.

Tku2: Unit 2—Thin blue-gray to blue-green devitrified tuff ~1 m thick overlain by brownish-gray–weathering, devitrified ash-flow tuff. Lithic component is mostly flattened pumice. Ranges from a few meters to ~90 m thick. K-Ar age, 14.1 Ma (Novak, 1984).

Tku1: Unit 1—Cliff-forming, crystal-rich, rhyolitic to trachytic ash-flow tuff grading upwards from densely welded, reddish-brown to less welded, brownish-gray lithic-crystal tuff. Contains flattened pumice fragments as large as 2.5 by 15 cm. Sanidine crystals as long as 10 mm, many of them adularescent, decrease in size, but increase in abundance, upwards. K-Ar age, 14.1 Ma (Novak, 1984). May be as thick as 120 m in an escarpment along Kane Springs Wash.

Tt: Trachyte (Miocene)—Black to grayish-purple, blocky-weathering trachyte lavas with a microcrystalline to glassy matrix that locally shows flow banding. In this map area, it is defined by the very hard layer that crops out in an otherwise poorly exposed slope. Flow is ~5 m thick in its only exposure in the mapped area. This flow is not considered part of the Kane Wash Tuff, but is found between units Tkw and Tku1.

Tkw: Unit W—Pinkish-gray, pale-yellowish-brown–weathering, rhyolite ash-flow tuff. Lower four-fifths of the unit is lithic tuff with non-compacted pumice fragments as much as 15 cm across, cavities, and few crystals; upper one-fifth of the unit is pink to pale-violet, moderately to densely welded cliff-forming devitrified lithic tuff. Thickness ranges from 137 m to zero. K-Ar age, 14.7 Ma (Novak, 1984).

Tko: Unit O—Largely moderate-brown to reddish-brown, densely welded, rhyolite ash-flow tuff easily recognized as forming a thin dark cliff under a thick light-colored slope. Eutaxitic structure is unique to most of this unit, and the flattened pumice fragments can be used for dip measurements. Maximum thickness of the unit is ~79 m in the Kane Springs Wash scarp decreasing to zero along south edge of the volcanic terrane. K-Ar age, 15.6 Ma (Novak, 1984).

Tb1: Amygdaloidal basalt (Miocene)—Dark-gray to grayish-black, brownish-black–weathering olivine basalt in compact to amygdaloidal flows. Single(?) aphanitic flow as much as 4 m thick exposed in the vicinity of Hackberry Canyon lies between the Hiko Tuff (unit Th) and crystal tuff of the Kane Wash Tuff (unit Tku). This basalt locally is coarsely amygdaloidal with epidote- and quartz-lined amygdules up to 1 cm long.

Th: Hiko Tuff (Miocene)—Pinkish- to brownish-gray, brown-weathering, moderately welded vitric-crystal to crystal ash-flow tuff, becoming slightly less welded toward the top of the unit. Basal 10–15 m, where exposed, is white to pale greenish-yellow and light-gray, partially welded, punky lithic-crystal tuff. In the upper half of the section there are local lenses of coarse impure sandstone or wacke as thick as 3 m. Maximum thickness is 43 m near Vigo. Hiko Tuff has yielded K-Ar ages of 18–20 Ma (Armstrong, 1970; Noble and McKee, 1972; Marvin et al., 1970).

Thh: Harmony Hills Tuff (Miocene)—Brownish-gray to pale yellowish-brown, reddish-brown–weathering, crystal-rich, biotite ash-flow tuff. Abundance and size of biotite crystals are diagnostic characteristics as the unit contains more euhedral biotite than any other ash-flow tuff in this region, usually in books as much as 3 mm in diameter and 1–2 mm thick. Total thickness of the Harmony Hills Tuff is ~81 m in Hackberry Canyon, where it rests on a basalt flow breccia (unit Tbb). Radiometric analyses of the Harmony Hills Tuff from the surrounding region yielded an average age of 21 Ma (Armstrong, 1970; Noble and McKee, 1972; Marvin et al., 1970).

Tbb: Basalt breccia (Miocene)—Thick, dark-purple, red, and black, monolithologic basalt flow breccias and flows. Well exposed in Hackberry Canyon and along the south edge of the volcanic terrane. The thickness of this unit is highly variable, with a maximum thickness reported by Cook (1965) of 289 m in an area 3 km west of Vigo; average thickness is closer to 100 m, thinning to zero away from Hackberry Canyon.

LEACH CANYON AND CONDOR CANYON FORMATIONS (Miocene)—In this area, consists of Leach Canyon Formation and Bauers Tuff (undivided), lacustrine limestone, and conglomerate.

Tlc: Leach Canyon Formation and Bauers Tuff, undivided (Miocene)—Bauers Tuff is a pale purple, highly welded tuff up to 8 m thick, but is too thin to show separately and is included with the underlying Leach Canyon Formation (Tlc). Leach Canyon Formation consists of a pale-lavender ash-flow tuff. The Leach Canyon consists of two cooling units locally separated by lenses of light gray, orange-mottled lacustrine limestone up to 5 m thick. Total thickness of unit is ~74 m west of Vigo. Age of the Leach Canyon Formation, based on K-Ar analyses of samples from the surrounding region, is ca. 24.6 Ma (Armstrong, 1970; Rowley et al., 1975).

Tl: Lacustrine limestone (Oligocene?)—Light-gray freshwater limestone in beds 10–30 cm thick, commonly containing algal structures. Thickness ranges from 5 to 30 m; typically 20 m thick. Occurs at the base of the volcanic section, resting unconformably on pre-Tertiary sedimentary rocks, and locally on, or interlayered with, prevolcanic conglomerate (unit Tc). Age is considered to be late Oligocene inasmuch as strata underlie lower Miocene tuffs (Ekren et al., 1977).

Tc: Conglomerate (Tertiary)—Reddish-orange– to reddish-brown–weathering, poorly sorted, synorogenic(?) conglomerate occurring in isolated patches filling low areas on the pre-volcanic erosion surface. Appears to interfinger locally with lower lacustrine limestone (unit Tl). Mainly well-rounded cobbles in a silty to coarse sandy matrix, but pebble- to small boulder–size clasts are present, all consisting of Paleozoic carbonate rocks, quartzite, and some chert. Thickness ranges from 0 to ~50 m.

MOENAVE AND KAYENTA FORMATIONS (Jurassic)

Jmk: Moderate-red to dark-red, fine-grained, nonmarine, silty sandstone and shaley sandstone present in poorly exposed, scattered outcrops along south edge of volcanic terrane.

CHINLE FORMATION (Upper Triassic)—Consists of Petrified Forest and Shinarump Members.

Ꞓcp: Petrified Forest Member—Moderate-red to dusky-red, fine-grained, nonmarine, silty sandstone and shaley sandstone present in scattered outcrops along the south edge of the volcanic terrane. Thickness is 365 m.

Ꞓcs: Shinarump Member—Grayish-red, dark-brown–weathering, ridge-forming, fine-grained sandstone and chert-pebble conglomerate. Some sandstone is cross-bedded and quartzitic. Fossil wood common elsewhere in the Shinarump was not seen here, and the overall texture of the member is finer than in exposures farther east. The Shinarump Member is observed to be 40 m thick in its sole outcrop within the map area.

Ꞓm and br: Moenkopi Formation (Middle? and Lower Triassic)—Predominantly gray, pale-brown, and yellowish-brown, grayish-yellow– to grayish-orange–weathering, even-bedded, dense marine limestone, with interbedded red, orange, and brown silty and shaley limestone giving large outcrops a color-banded aspect. Moenkopi rests with slight angular discordance on a variety of units, including br, Pk, and Pt, and locally lies directly on unit Pr5. Unit br is a dark-brown–weathering, chert-rich, sedimentary or karst breccia that is locally present in lenses along the base of the Moenkopi. Upper contact with the Shinarump Member of the Chinle Formation (unit Ꞓcs) is poorly exposed in an isolated outcrop, but 985 m of Moenkopi is present in the homoclinal section 5 km west of Vigo.

Pk: Kaibab Limestone (Lower Permian)—Gray limestone with ~50% brown-weathering chert. Chert is commonly bedded, but can occur as elongate nodules. Thickness ranges from 40 m to zero.

Pt: Toroweap Formation (Lower Permian)—Pinkish-gray to light gray, cliff-forming limestones with minor chert. Minimum thickness of 60 m lies unconformably between the Moenkopi Formation (unit Ꞓm) and Permian red beds (unit Pr 5).

RED BEDS (Lower Permian)—Red sandstone unit, subdivided here into units 1–5. Complete red bed section is exposed, with a total thickness of ~552 m. This unit correlates approximately with strata mapped as Coconino Sandstone, Queantoweap Sandstone, and Pakoon Limestone of McNair (1951) in the Beaver Dam Mountains to the east (Reber, 1952; Langenheim and Larson, 1973).

Pr5: Unit 5—Slope-forming, even-bedded, red, coarse-grained sandstone and silty sandstone. Lower contact is drawn at the base of a prominent gray carbonate marker bed that is overlain by yellow sandstone beds. Upper contact is drawn at the discordant contact with either overlying chert breccia of the Toroweap Formation and Kaibab Limestone (units Pt and Pk) or carbonate beds of the Moenkopi Formation. Unit is ~123 m thick.

Pr4: Unit 4—Upper 90 m is red, slope-forming, coarse-grained sandstone containing some interlayered red siltstone layers, as well as minor resistant beds of gray, fossiliferous limestone. These beds are darker red and more resistant than the sandstone beds of unit Pr5, and have significantly less carbonate that unit Pr3. The lower part of this unit consists of badland-weathering, contorted beds of red and yellow shaley sandstone and siltstone with interlayered beds of gypsum. Gypsiferous beds up to 6 m thick occur in an area ~1100 m long by 305 m wide (Jones and Stone, 1920) and appear to represent deformed evaporite basin deposits. The thickness of this unit is ~242 m.

Pr3: Unit 3—Even-bedded, pink, white, and gray sandstone and shale, with lesser gray limestone and sandy limestone and cross-bedded pale-brown sandstone. Contains more pink beds and fewer carbonate beds than units Pr1 and Pr2. The upper contact is defined at the top of the highest carbonate bed. This unit is ~90 m thick.

Pr2: Unit 2—Pink, white, and gray sandstone, gray limestone and sandy limestone, cross-bedded pale-brown sandstone, pinkish shale, sandstone, and sandy limestone, with calcareous beds increasing downwards. This unit contains a higher percentage of gray carbonate beds than units Pr1 and Pr3. Thickness is ~50 m.

Pr1: Unit 1—Even-bedded, pink, white, and gray sandstone, gray limestone and sandy limestone, and cross-bedded pale-brown sandstone, with lesser pinkish shale, sandstone, and sandy limestone. This unit has more carbonate beds than units Pr2 and Pr3, and is more pink in color than unit Pr2. Basal contact is drawn at the lowest red sandy bed. Thickness is ~45 m.

BIRD SPRING FORMATION (Pennsylvanian to Mississippian)—Divided into units 1–3.

MPb3: Unit 3—Light to dark-gray limestone, with very little chert. Looks very similar to the top of unit MPb1, and is often distinguished solely on stratigraphic position. Thickness is ~30 m.

MPb2: Unit 2—Very fine-grained, brown-weathering sandy limestone. Well exposed in Meadow Valley Wash near Galt. Thickness is 30–45 m.

MPb1: Unit 1—Interlayered beds of light- to dark-gray limestone, pinkish-gray cherty limestone, reddish-brown sandy, calcareous, and dolomitic limestone, and white to reddish-brown, fine-grained sandstone. Limestone is fine to medium crystalline, thin to medium bedded, and fossiliferous. Sandy beds, some of which are quartzitic, form brownish- to reddish-weathering ledges in even-bedded step-like outcrop. Upper limestone and cherty limestone are middle Wolfcampian in age. The lowermost limestones and cherty limestones are Morrowan in age. A complete continuous section is not exposed anywhere in the Meadow Valley Mountains, but the unit was previously estimated to be ~1310 m thick (Tschanz and Pampeyan, 1970); however, it may be closer to 2000 m thick in the southern Meadow Valley Mountains.

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